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FLUVIAL GEOMORPHOLOGY APPENDIX

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Fluvial geomorphology is the study of landform evolution related to and, as an integrative field, includes the related disciplines of hydrology, hydraulics, sediment transport, soil mechanics, and the mechanical effects of vegetation. Any project that potentially affects natural stream processes requires a basic understanding of the fluvial geomorphology of the system in question.

1 BASIC CONCEPTS IN FLUVIAL GEOMORPHOLOGY

1.1 Spatial and Temporal Scale

When evaluating a stream channel, it is important to consider both the spatial and temporal scale at which an evaluation or investigation is conducted, as well as the scale of the inputs and processes affecting the stream channel. Stream channels are dynamic systems and are constantly changing both spatially and temporally. Different reaches of a stream are dominated by varying relationships between inputs and geomorphic processes.

There is a hierarchy of variables affecting stream systems. The foundation of this hierarchy is the triad of climate, geology, and topography, a suite of variables that together are termed lithotopo units[1]. This triad of variables determines channel fluvial processes, which are manifest in the form of independent variables affecting stream channels – hydrology, sediment supply, and in some cases the supply of large wood. These independent variables are typically fairly constant in a temporal scale, but can vary dramatically on a spatial scale within a watershed.

The channel processes and character that are determined largely by the lithotopo unit on a spatial scale, in turn influence habitat characteristics of the channel[2]. The variables that define the lithotopo units typically change downstream through the watershed, resulting in predictable spatial variability in habitat form and function. The downstream change in hydrologic regime through a watershed can be generally described as an increase in volume accompanied by a decrease in the extent and rate of change of flows. Within a channel reach, however, there is generally no appreciable spatial variability in hydrology. Sediment transported can be generally described as increasing in volume downstream, but decreasing in particle size. Local variations in geology and bank material, as well as depositional patterns, may result in highly variable sediment character on a reach scale.

On a temporal scale, stream channel form and process are affected by climate change or cyclical fluctuation (such as drought), seasonal weather variations, and anthropogenic watershed impacts. Climate change typically occurs over decades, though cycles of climate patterns may occur on a scale of years. On all temporal scales, only climate and geology function independently, driving all the other variables. Climate change is one of the most obvious and ongoing disturbance mechanisms affecting stream channels, though it may take decades or centuries to manifest and is a complex phenomenon that cannot be accurately assessed over a short period of time. Over short time scales (one to 10 years) discharge and sediment load become independent variables.[3] At this scale, some disturbances caused by human activities can be assessed. For example, overgrazing can affect hydrology and sediment load, potentially causing channel erosion and incision and resultant habitat degradation. Defining the temporal scale of observation, therefore, is essential for assessing relationships among various attributes of fluvial systems.

Habitat form and function is also significantly influenced by and dependent upon disturbance to the channel system. White and Pickett[4] define disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". The combination of predictable variability in inputs (such as seasonal variations in hydrology) and less predictable disturbance regimes (such as landslides and fire) result in unique suites of geomorphic processes and inputs that dictate physical habitat structure and dynamics.

1.2 Equilibrium

A basic concept in fluvial geomorphology is that stream channels tend toward an equilibrium state in which the input and output of mass and energy to and from a specific reach are equal.[5] A corollary to this is that overall channel morphology remains relatively constant throughout the transfer of mass and energy, assuming inputs to the channel are relatively constant. The term equilibrium in the context of stream channels refers to the relative stability of the channel system and its ability to maintain its morphological characteristics over some period of time and range of flow conditions, accommodating minor variations in inputs. In reality, perfect equilibrium does not exist in natural streams. However, natural streams do tend to develop channel sizes and shapes that accommodate and reflect the typical hydrologic regime and the character and quantity of sediment supplied by the watershed. These streams are said to be in a state of approximate equilibrium.[6]

Numerous authors[7][8][9][10] have presented discussions on and defined variations on the concept of equilibrium. Definition of the various forms of equilibrium is dependent upon the time scale under which equilibrium is scrutinized, and the same channel process may be defined as differing forms of equilibrium, or even as non-equilibrium, simply by virtue of differing periods of observation. Due to the complexity and variety of definitions of varying forms of equilibrium, these variations are not defined here. For further discussion of equilibrium, refer to Graf, 1988[11].

Stream channels commonly exhibit many forms of equilibrium, and are subject to changes in equilibrium resulting from anthropogenic influences, catastrophic events, and gradual changes in climate. For example, short-term fluctuations in a given variable, such as channel depth, may occur throughout the channel system, but the longer-term, constant mean value of the variable is maintained. An example of this occurs when channels adjust to scour and fill associated with seasonal flooding. It is important to note that the time scale of observations is critical for defining an equilibrium state – if the time scale is too short, the mean value of the variable in flux will not be accurately determined. Following a low probability flood (50-year flood), a given reach of channel may exhibit bed degradation and bank erosion. However, in subsequent years, the bed and banks may recover to previous channel dimensions. If observed only over a single year following a flood, the channel will not appear to be exhibiting equilibrium conditions. If observed over a decade following the same flood, the channel would otherwise exhibit equilibrium conditions.

Similarly, a stream may adjust its character gradually in response to gradual environmental change, such as a slow change in base level (the level below which a stream cannot erode, such as a lake at the channel mouth or a bedrock sill). In this instance, the stream undergoes a complex pattern of erosion, deposition, changes in sediment load and renewed incision as it adjusts to the new base level. The time scale through which equilibrium is exhibited may span hundreds or thousands of years. At any given point in time during the adjustment, the channel may exhibit equilibrium conditions; though over time the equilibrium changes. This is referred to as *dynamic equilibrium*.

Human influences on channels and their inputs can affect rapid destabilization of equilibrium conditions, or force rapid change of equilibrium values. Human influences are varied and complex and can affect all variables influencing channel equilibrium, channel processes and habitat. The most common and drastic human influences are related to urbanization, and include changes to the hydrologic regime and imposing constraints on the channel, such as levees, walls or culverts. Removal of large wood from the channel is also common, and can have significant impacts on channel processes and habitat.

1.3 Channel Pattern

While researchers have variously classified channel patterns[12,13,14]. The large variety of channel patterns resulting from complex suites of controls, inputs, and processes can be reduced to three basic types of equilibrium channel pattern - straight, meandering, or braided. Equilibrium channel pattern is dictated by complex interaction of numerous channel variables. However, equilibrium channel pattern can be largely explained in most rivers by the interaction of channel slope, bankfull discharge, and available sediment load[15].

Straight channels are rare in nature, as the channel thalweg (deepest portion of channel) typically wanders from bank to bank within even a straight channel. Straight channels usually exist only in narrow valleys where geologic control prevents meandering and are dominated by sediment transport and colluvial processes. Meandering channels, by contrast, wander back and forth across the channel and are typically alluvial in character. Both straight and meandering channels consist of a single channel thread. Braided channels differ in that they exhibit numerous channel threads separated by islands or bars, which are often submerged at high flow. Braided channels are dominated by sediment deposition processes and are alluvial.

1.4 Regime Theory and Channel Geometry

Prior to extensive use of equilibrium principles by geomorphologists, hydraulics engineers used the concepts of equilibrium in *regime theory*.[16] Regime theory is based on the tendency of a stream system to obtain an equilibrium state under constant environmental conditions. It consists of a set of empirical equations relating channel shape to discharge, sediment load and bank resistance. The theory proposes that dominant channel characteristics remain stable for a period of years and that any change in the hydrologic or sediment regime leads to a quantifiable channel response (such as erosion or deposition). Stream reaches that are "in regime" are able to move their sediment load through the system without net erosion or deposition and do not change their average shape and dimensions over a short time period.[17] By definition, regime theory is not applicable to streams located in landscape positions where either erosion or deposition is the dominant process, such as alluvial fans, deltas, or headwater source areas.

Regime theory formed the basis for a large body of work in fluvial geomorphology focusing on identifying and defining the geometric properties of equilibrium alluvial channels and their adjustments to discharge and sediment transport regimes.[18] According to R. D. Hey,[19] there are nine measurable variables used to define equilibrium channel geometry. These characteristics are considered dependent variables for stream reaches in regime:

1. Average bankfull channel width (w),
2. Average bankfull depth (d),
3. Maximum depth (d_m),
4. Average bankfull velocity (V),
5. Height (Δ) of bedforms,
6. Wavelength (λ) of bedforms,
7. Channel slope (S),
8. Meander arc length (z), and
9. Sinuosity (P).

The six independent variables that control changes in channel dimension and shape are:

1. Discharge (Q),
2. Sediment load (Q_s),
3. Size of bed material (D),
4. Bank material and character,
5. Bank and floodplain vegetation (riparian and/or upland species), and

6. Valley slope (S_v).

Changes in any of these controlling variables may result in a new channel geometry that represents a stable morphology in a new equilibrium state.

1.5 Geomorphic Thresholds

Short-lived states of disequilibrium often result when a geomorphic threshold is exceeded. As defined by S. A. Schumm,[20] a geomorphic threshold is a condition of landform stability that is destabilized by a progressive change in an external or independent variable. This occurs at the moment in time and space at which forces and resistance are equal. The classic example of a geomorphic threshold is the attainment of critical shear stress in a channel during increasing discharge. In such case, channel bed stability is maintained through increasing discharge until a threshold of shear is exceeded. When the threshold of critical shear is exceeded, sediment motion is initiated and sediment transport ensues.

Both extrinsic and intrinsic geomorphic thresholds exist. An extrinsic threshold is exceeded by application of an external force or process, such as a change in sediment supply or discharge. Progressive change in the external force triggers an abrupt, physical change in the system. Examples of forces relating to extrinsic thresholds are climatic fluctuations, land-use changes, and base-level changes. An intrinsic threshold is exceeded when system change occurs without a change in an external variable; the capacity for change is intrinsic within the system and can be considered the systems natural variability. An intrinsic threshold might be reached when a torturous meander bend becomes unstable, resulting in a meander cutoff and subsequent reduction in sinuosity.[21]

The most significant controls on channel stability over a period of years or decades are flow regime, sediment supply, and vegetation. If any of these controls changes (either progressively or suddenly), the channel may cross a threshold and undergo change. Channel avulsion, the formation of a new channel across the floodplain, and channel degradation, the general lowering of channel-bed elevation, are two common types of channel changes involving geomorphic thresholds.

1.6 Channel Responses to Change in Dependent and Independent Variables

Rivers are complex systems of inputs and response whose features and form are rarely constant. Explanation and prediction of their behavior requires great depth in understanding of historic condition and current morphology and process, at times involves considerable educated speculation, and is always uncertain and prone to risk. Schumm (1984) [22] describes in detail seven considerations for thoroughly evaluating channel response. These include the following:

1. *Scale*. Both time and space must be considered in both explanation and prediction. As discussed previously, the time scale and spatial scale considered may result in varying

conclusions regarding channel response to change in variables and inputs. Generally for time scales, the shorter the time period, the greater the ability to explain response mechanisms or make accurate predictions. Similarly, on a spatial scale, the larger the area, the greater the difficulty in explanation or prediction.

2. *Location*. The location of the reach or site under investigation must be considered relative to its surroundings and the influences they exert on inputs and controls.
3. *Convergence*. Convergence is a phenomenon whereby differing causes and processes may result in the same result, thereby confounding explanation or extrapolation/prediction. For example, a stream may incise due to a change in hydrology, a reduction in sediment supply, or a steepening of channel slope.
4. *Divergence*. Divergence is a phenomenon whereby similar cause or process may result in different results, similarly confounding accurate prediction or explanation of response. For example, urbanizing hydrologic regime may lead to channel incision, or if sufficient grade control exists, may widen laterally.
5. *Singularity.* Singularity refers to the specific qualities of a stream that separate it from other similar streams. Many streams may be classified as equal channel types, yet may have specific attributes and responses or response times that cannot be predicted by these channel types.
6. *Sensitivity.* Sensitivity refers to the susceptibility of stream systems to external changes and disturbance. A similar or equal external change will have varying effects on different streams. A minor external change may result in either no response or major response. Sensitivity is closely related to scale, location, and to geomorphic threshold concepts.
7. *Complexity*. Stream channel processes are a complex interaction of many variables, thus responses to changes in those variables is often complex. Adjustment to changes in external variables may not occur progressively, but rather it will likely occur iteratively and result in numerous internal responses and counter-responses before settling at a new equilibrium.

Channel response to external change in inputs or controls may occur in any dimension – laterally, vertically, or longitudinally. On the horizontal plane, streams may migrate laterally without a change in width (meandering), or they may change laterally through channel widening or narrowing. On the vertical plane, rivers incise and aggrade. As indicated by Schumm's seven problems of evaluation of geomorphic response, the factors leading to these responses are complex and highly dependent upon scale, location, and sensitivity. The scale (temporal and spatial) influences the causal relationships among fluvial variables.

In spite of the complexity of predicting or explaining geomorphic response, there are a number of common generalized channel responses that can be attributed, at least theoretically, to distinct causes. These include aggradation, degradation, lateral migration, and avulsion.

1.6.1 Aggradation

Aggradation is the progressive accumulation of in-channel sediment resulting in increased channel bed elevation. Aggradation is a response to channel system changes that reduce the channel's capacity to transport the sediment delivered to it. Generally, this occurs as result of either increased sediment supply (load or gradation) or diminished stream power (transport capacity).

Aggradation associated with increased sediment supply may occur in response to any of the following conditions:

- Increase in sediment size or volume associated with landslides or other geologic disturbances
- Increase in sediment volume inputs from hillslope disturbances including vegetation removal, fire, and agricultural and other land use impacts
- Increase in sediment volume inputs from excessive bank erosion

Aggradation associated with decreased stream power may occur in response to any of the following conditions:

- Local dams (including beaver and log jams) reduce channel slope
- Large dams reduce duration of transport discharge
- Diversions reduce discharge
- Split flow within a channel reduces discharge in each split channel
- Reduced channel slope associated with local dams or grade control placed above grade (beaver dams, log jams, culverts, etc.)

1.6.2 Channel Degradation

For a complete discussion of channel degradation and incised river channels, refer to Darby and Simon, 1999[23].

Channel degradation is the inverse of aggradation and involves the progressive lowering of the channel bed relative to its floodplain elevation. Degraded channels (also called entrenched, eroded, or incised channels) occur when stream power exceeds the channel bed's resistance, or when sediment transport capacity exceeds the sediment supply. The process of degradation begins when stream power exceeds a threshold condition of bed stability[24].

Channel degradation may occur in response to any of the following conditions:

- Stream channelization and straightening causing a steepening of the channel profile
- Lowering of base level, such as the lowering of a lake, removal of grade control (culvert, bedrock, log controls)
- Increase in duration of transport flows associated with vegetation removal, urbanization, or other forms of land development that increases runoff rates and volumes
- Concentration of high flows within the channel due to encroachment of walls, structures, or levees
- Upstream dams may cause sediment "starvation" (though this is usually balanced with reduced

critical flow durations)

Regardless of the causes of degradation, the response pattern of incised channels is remarkably similar throughout a variety of stream environments. Incised-channel evolution models are useful for tracking landform development through time. Schumm et al. [25], used such a model to develop a channel-evolution sequence for a stream in Mississippi. The model assumed that the base level for the channel did not change, and that land use in the watershed remained relatively constant. The model (see Figure Geomorph - 1[26]) described five channel reach types (Types I to V) whose conditions ranged from disequilibrium (Type I) to a new, dynamic equilibrium (Type V).

Figure Geomorph - 1. Diagram of a channel evolution model. (*From ISPG*)

This model portrays a very common subsequent phenomena of channel degradation – channel widening. As a stream channel degrades, its capacity increases and stream energy becomes concentrated within the channel, rather than dissipating on the floodplain. Additionally, bed erosion can destabilize stream banks by undermining the bank toe. The combination of increased energy within the channel and reduced bank stability often leads to rapid bank erosion.

1.6.3 Lateral Channel Migration and Erosion

Channels migration is the progressive movement of a channel across a valley and involves bank erosion and transport of eroded materials. Lateral channel migration may occur within the context of equilibrium, provided that channel form does not change overall. However, lateral migration may also occur in response to disturbance or external changes in input variables. Lateral migration may be initiated or exacerbated by the following conditions:

- Hardening of channel banks upstream or across the channel may reduce the channel's capacity to adjust locally, and may transfer the excess energy
- Channel aggradation often results in lateral migration as the channel seeks to maintain its capacity
- Channel degradation often leads to lateral migration
- Riparian and channel bank vegetation removal may reduce the banks resistance, leading to erosion

1.6.4 Channel Avulsion

Channel avulsion is a major change in channel direction or location. The mechanism by which avulsion occurs is generally through headcutting and scour of a new channel through the floodplain. This headcutting and scour may be initiated during overbank flows associated with large floods, logjams, beaver dams, or ice jams. Avulsion generally occurs when other channel conditions increase the volume of flow across the floodplain relative to the channel itself, thereby increasing the erosional forces on the floodplain. Aggradation within the main channel or a blockage of the main channel are the primary conditions under which flow energy increases on the floodplain. Similarly, flow restriction within the floodplain that concentrates flow within a narrow area may result in energy conditions that lead to avulsion during overbank flows.

Avulsion occurs in numerous types of channels[27]. Meandering channels may avulse due to insufficient sediment transport, which results in channel aggradation and further loss of channel capacity. Aggradation increases the frequency of overbank flows and avulsion potential. Topographic variability on the floodplain surface can also concentrate overbank flows in certain areas and create further avulsion potential. Avulsion potential is also increased if floodplain roughness is relatively low compared to the active channel roughness, which is common in areas where the floodplains have been cleared for agriculture. Finally, all channels are prone to avulsion if they become perched relative to their floodplain. This is common in alluvial-fan environments or along relocated channel segments.

2 SED TRANS SECTION (THIS SECTION IS A SEPARATE DOCUMENT FILE)

3 VEGETATION AND WOODY DEBRIS IN FLUVIAL PROCESS

Vegetation affects the geomorphologic process and resultant forms by controlling a number of variables affecting process, and by contributing material to the stream system. Because the type of vegetation that occurs naturally is a function of geology, topography, and climate, riparian vegetation character can act as a key independent variable in determining channel form and process. Riparian vegetation plays a key role in maintaining a stable channel form by stabilizing streambanks and dissipating energy along the banks. The growth of riparian vegetation in or near the channel also facilitates floodplain formation as vegetation increases hydraulic roughness, reduces erosion and promotes sedimentation. Upland vegetation also can play a role in channel process by controlling hillslope erosion, thereby reducing sediment input to stream channels.

Both upland and riparian areas also contribute vegetative debris to the channel. The role of large woody debris in channels is now recognized as a critical factor affecting geomorphology in forested environments and as a potential component of channel design[28][29]. Coarse or large woody debris in streams represents large roughness elements that divert flowing water and influence the scour and deposition of sediment in forested streams throughout the world. Large woody debris in stream channels results from trees that fall from banks or hill slopes. Processes that initiate tree fall include wind throw, bank erosion, channel avulsion, tree mortality, mass wasting and land-use practices such as logging.[30] The introduction of large woody debris into the channel affects both channel form and process by:

1. Creating steps in the longitudinal profile of the streambed, thus dissipating energy, aiding in formation of both pools and riffles, and increasing sediment storage[31];
2. Improving fish habitat by increasing types and sizes of pools[32] (pools associated with woody

debris may be deeper and have more depth variability than free-formed pools[33]);

3. Forming channel bars and creating suitable sites for spawning (this influence has not been extensively studied)[34]; and
4. Promoting sediment deposition along the active channel and floodplain, which provides sites for riparian vegetation colonization, the growth of forested islands in the channel and forest floodplain development.[35]

The geomorphic effects of woody debris vary with stream size. In low-order streams (first and second order), woody debris elements are large relative to the stream and may cause significant channel migration or widening and sediment storage. In high-order streams (fifth order), where woody debris elements are small relative to the channel, woody debris accumulations may increase channel migration and the development of secondary channels, although islands formed as a result of large woody deposits may actually increase stability (Abbe, 1996??).[36]

Placeholder – insert diagram of stream order to be inserted at 90%

4 ASSESSMENT METHODOLOGIES

4.1 Baseline Geomorphic Analysis: Evaluation of Existing Conditions and Historic Change Where Restoring Historic Configuration is Appropriate

The most important components of geomorphic analysis include:

- Assessment of past channel change,
- Determination of causes of channel change, and
- Assessment of ongoing channel adjustments.

Habitat restoration and streambank protection projects will likely be unsuccessful if the driving forces of channel adjustments are not recognized and addressed. Consequently, streambank-protection and habitat restoration projects designed to mimic or alter natural channel processes require an understanding of the causative agents of change.

4.1.1 Characterizing Existing Channel Conditions

The initial characterization of the project reach should be based on plotted bed profiles and maps or aerial photographs that show channel planform. The project reach should be described in terms of channel slope, pattern, sinuosity, and cross-sectional dimensions. Infrastructure controls should be identified and their geomorphic relevance indicated, such as fixed-bed elevations (pipelines, weirs, bridge aprons) or areas of channel or floodplain encroachment (roads, development, bridges, culverts, levees).

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4.1.1.1 Channel Slope

Channel slope is defined as the vertical fall of a stream over a given distance. It is typically reported as a percentage (ft/ft) or as feet of drop per mile (ft/mile). Channel profiles (elevation vs. distance plots) depict slope trends on a stream system. The most accurate means of determining the slope of the channel bed is by surveying the channel thalweg elevation (the deepest point in the channel bed) through a reach. Alternatively, longitudinal profiles may be obtained from the Federal Emergency Management Agency if a hydraulic model has been developed for flood-insurance studies. Channel profiles determined from topographic maps may be accurate in some situations, but may not be detailed enough, since contour lines generally reflect the water surface rather than the channel bed, and for smaller streams may actually represent the canopy cover. Furthermore, topographic maps are based on survey data which may predate significant changes in the valley topography and the channel.

Channel slope is always measured in terms of the channel distance, rather than the valley distance, and can be calculated by the following equation:

$$S=(E_2-E_1)/D$$

Where, S = channel slope, E_2 and E_1 = channel bed elevations (in feet or meters) at two points along the thalweg, and D = channel distance between E_2 and E_1 (in feet or meters). A more accurate representation of channel slope will be attained if survey points are located from the top of one riffle to the top of another riffle (thereby including the entire channel unit), rather than between a riffle and a pool. The longer the survey length, the more accurate the slope calculation will be, unless a significant valley control is crossed.

4.1.1.2 Channel Planform

Channel planform is the form of a stream as seen in map (aerial) view. In streams with meandering patterns, planform is quantitatively described in terms of sinuosity by the equations:

$$P=D_c/D_v \text{ or}$$
$$P=S_c/S_v$$

Where P = sinuosity, D_c = channel length (feet or meters), D_v = valley length (feet or meters), S_c = channel slope, and S_v= valley slope. Channel length is measured along the channel thalweg or, if necessary, the channel centerline.

Other parameters that describe channel planform are the belt width, wavelength, amplitude, and radius of curvature of an individual meander bend (Figure Geomorphology 2). Collectively, these planform characteristics can be compared to historical conditions in order to assess channel behavior over time.

Figure Geomorphology-2. Channel planform characteristics. From ISPG appendix

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4.1.1.3 Channel Cross-Section

Channel cross-section reflects the two-dimensional view across the channel, typically viewed in the downstream direction. A set of surveyed cross-section points should include, at a minimum, floodplain elevation, top of bank, bank toe, lower limit of vegetation, and thalweg. Typical dimensions measured from a channel cross-section include top width, bank height, bank slope, and channel depth. By convention, the right and left banks reflect the sides of the channel as viewed in the downstream direction (Figure Geomorphology-3).

Figure Geomorphology -3. Channel cross-section. From ISPG appendix

4.1.1.4 Pools and Riffles

Pools and riffles generally occur at relatively constant spacing in alluvial streams. A pool-riffle sequence is a dynamic response of the channel to a large-scale, non-uniform distribution of three variables: velocity, boundary shear stress and sediment.[37] L. B. Leopold et al. (1964), determined that riffle spacings were consistently on the order of five to seven times the channel width (Figure Geomorpholgy-4).[38] This empirical deduction is consistent with a theoretically predicted spacing of 2π (6.28) times the channel width determined by R. D. Hey.[39] Hey and C. R. Thorne further substantiated the correlation between width and riffle spacing, predicting riffle spacing as:

$$z = 6.31w$$

where z = the distance of riffle spacing, and w = bankfull width[40]. This definition of riffle spacing is based on work in Great Britain on gravel-bed rivers with single-thread channels and a mix of straight, sinuous, and meandering planforms. The coefficient of determination for this data set is 0.88, and the overall range of riffle spacing for the majority of sites is between four and ten times the channel width. As such, measured riffle spacing may not be an effective evaluative tool, but rather may be a useful design tool.

Figure Geomorphology-4. Riffle spacing as a function of bankfull width. From ISPG appendix

4.1.2 Channel Classification

A classification of reaches can aid in visualizing and describing the project site, although classifications on their own provide limited application for channel restoration designs.[41] Early classification systems were based on channel planform patterns (e.g., those developed by Leopold and M. G. Wolman[42]), including meandering, braided and straight channel patterns. Later classification systems were also based on channel form, including cross-sectional geometry, longitudinal profile and size/composition of bed material (e.g., those developed by D. L. Rosgen[43]). Process models such as Schumm, Harvey, and Watson's Channel Evolution Model attempt to link channel process, form and stability.[44,45,46] Finally, Montgomery and Buffington's classification[47] is based on a hierarchy of spatial scales that reflect different geomorphic processes and controls on channel morphology. This system (which includes geomorphic provinces, watersheds, valley segments, channel reaches and channel units) provides a useful means for comparing channels at increasingly finer spatial scales.

Rosgen's classification system is the most extensive and widely recognized. To date, this system for stream classification is probably the most useful for communicating about channel systems. This system divides streams into seven major and 42 minor types based on channel pattern, bed material size, slope, entrenchment, width to depth ratio, and sinuosity. Major channel types are subdivided based on the channel slope and dominant type of bed and bank materials. This classification system does not, however, necessarily reflect differences in channel process or channel genesis. Because some of the thresholds for class divisions are not based on differences in channel genesis or process, it is limited in its applicability to design of process- and function-oriented stream restoration or bank protection.

It is important to note that most classification systems are based on the existing channel morphology of a stream, which may or may not be in equilibrium. A classification system must be used with the understanding that fluvial systems are constantly adjusting and evolving in response to changes in slope, hydrology, land use and sediment supply.

4.1.3 Assessing Historic Channel Change

4.1.3.1 Aerial Photography

When available, sequential photos of a stream channel over the last 100 years provide a historical record of channel planform changes. This information, coupled with hydrologic data from stream gauges, is extremely valuable for understanding how the particular channel responds to floods. An evaluation of historic channel change may reveal previous channel conditions that provided quality habitat or channel stability, which may then be used as the basis for project objectives. However, an aerial photo provides a snapshot in time and does note necessarily imply channel stability. The stream may have been responding to significant changes in the watershed, or may have been stable under different watershed conditions. There is no reason to assume that a past morphological form will be stable under current hydrologic and landscape conditions unless watershed conditions have remained relatively constant, which is rarely the case.

Aerial photographs for areas in the western United States are available beginning in the 1930s typically and are recorded in a database maintained by the U.S. Geological Survey Earth Science Information Center (the USGS will search for historical photography at *1-888-ASK-USGS*). Access to maps and photographs produced by USGS can be found at http://mapping.usgs.gov. Aerial photographs of your region can be obtained from the Washington State Department of Natural Resources, the Washington State Department of Transportation, the Federal Bureau of Land Management, the U.S. Forest Service, the U.S. Army Corps of Engineers and the Natural Resources Conservation Service.

4.1.3.2 Ground Reconnaissance

Field observations provide valuable information regarding flood history and channel response. This information is especially valuable when combined with hydrologic data regarding flood-recurrence intervals – for example, the effects of a recent 10-year or 25-year recurrence-interval event might be directly observed in the field. Ground assessment of stream channels may include observable flood impacts, such as abandoned channels, natural channel cutoffs or the accumulation of woody debris on mid-channel bars. Many geomorphic channel features can be roughly dated according to the age of riparian vegetation that is present. For example, an abandoned side channel with 10-year-old cottonwoods present may represent the impacts of a flood documented 10 to 11 years ago. Ground reconnaissance is an essential part of a geomorphic assessment and can provide useful information on the geomorphic effects of large flows in a particular channel reach.

4.2 Advanced Geomorphic Analysis: Achieving Geomorphic Stability Where Historic Configuration is Inappropriate

Alluvial streams are highly dynamic and responsive to changes in hydrology, slope or sediment load. Historically, engineering projects have dramatically destabilized stream channels by imposing unnatural and inappropriate channel cross-sections, slopes, discharges and sediment transport regimes. The destabilization of streams occurs when the balance between transport energy and sediment supply is altered. If a project is designed to modify hydrologic or hydraulic regimes, sediment transport continuity should be a primary project objective.

Geomorphic stability occurs when the channel conveys flow and sediment without undergoing net erosion or deposition. Successful bank-protection and habitat restoration projects promote that balance and provide for optimal channel function and aquatic habitat. One of the most significant challenges in streambank-protection and habitat restoration projects is defining this state of channel equilibrium and directing the project to promote long-term channel stability. In the context of geomorphology, this assessment requires an evaluation of current channel conditions, an assessment of historic changes that may have resulted in channel destabilization, a determination of the mechanism and causes of destabilization and an estimation of conditions required to promote sediment transport continuity. Additionally, it is important to determine whether the existing hydrologic regime is stable or if there will be continued change over time – i.e. additional development in urban areas.

4.2.1 Channel Stability

The assessment of channel stability relates the current sediment transport capacity of the channel to the existing sediment supply. Excessive transport capacity results in channel degradation, which is commonly indicated by geomorphic features such as headcuts (steep breaks in channel profile), human activities such as extensive channel armoring, or bank over-steepening and gravitational failure. Channel degradation can result in a floodplain surface becoming high enough above the channel that it is no longer inundated by the current hydrologic regime (see Figure Geomorphology –5). The formation of such a perched floodplain, or terrace, disconnects that surface from the water table and affects the establishment and survival of riparian vegetation. Other effects include unstable banks due to oversteepening, bank instability due to groundwater discharge, increased shear stress because of low-probability flows being contained within the channel, and loss of wetland/floodplain habitat and backwater areas. This process is often coupled with the progressive formation of a new floodplain surface within the incised channel. Excessive sediment supply is generally evidenced by aggradation such as pool infilling, loss of channel capacity, overbank deposition, channel widening and extensive channel bar development. Sediment transport evaluations, such as incipient motion and sediment continuity modeling, assess the mobility of sediment in a given system and can analyze reach stability. Sediment transport evaluations are further discussed in sections ……

4.2.2 Causes of System Degradation

A geomorphic assessment of the reach where the streambank-protection and habitat restoration project is intended will provide some understanding of the causes and effects of channel change through time. This assessment includes quantifying historic changes via repeat bed profiles, maps, as-built bridge-survey data and sequential aerial photographs. Potential causes for geomorphic channel change include alterations in hydrology or sediment load, the occurrence of large floods and human activities such as urbanization and channelization. After completing the geomorphic assessment, the next step is to estimate geomorphic parameters that will provide for channel stability under project conditions. These steps, in combination with hydraulic analyses, then lead to the definition of design elements such as channel slope, planform and cross-sectional geometry.

Comment: This discussion underemphasizes the driving force of fluvial geomorphology: energy & its dissipation. Most 'healthy' stream systems with high quality habitat and other attributes that we value are distinguished by 'sophisticated', complex energy dissipation mechanisms (e.g., form roughness and other means of dissipating energy internally, such as large woody debris). Conversely, streams that we generally consider degraded have lost their structural complexity and are dissipating energy through excessive sediment transport and/or skin roughness (e.g. downcutting widening, braiding).

Similarly underemphasized is the importance of accessible floodplains. The channel characteristics discussed as providing balanced inputs & outputs of sediment are possible because excess flows leave the channel during high flow events – dissipating their energies over *a wide area instead of concentrating them in the channel. This is essential to the geomorphology of alluvial systems and really cannot be overemphasized.*

Finally, the role of vegetation is also shorted. As the 'skin' of the riparian, floodplain, and upland areas, vegetation provides critical stabilizing and roughening functions that make possible the existence of channels with high aquatic habitat value, that is, those with high hydraulic and structural complexity.. Not to mention the role of floodplain vegetation in trapping and stabilizing fine sediments, bank building, bank storage, etc.

Collectively, the energy-dissipating functions of floodplains and vegetation are (largely) what maintain the system's ability to balance the inputs and outputs of water, sediment, and kinetic energy.

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